Observation of the $B_s^0 \rightarrow \eta' \eta'$ Decay

R. Aaij et al. (LHCb Collaboration)

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The first observation of the $B_s^0 \rightarrow \eta' \eta'$ decay is reported. The study is based on a sample of proton-proton collisions corresponding to 3.0 fb$^{-1}$ of integrated luminosity collected with the LHCb detector. The significance of the signal is 6.4 standard deviations. The branching fraction is measured to be $[3.31 \pm 0.64 \text{(stat)} \pm 0.28 \text{(syst)} \pm 0.12 \text{(norm)}] \times 10^{-5}$, where the third uncertainty comes from the $B^+ \rightarrow \eta' K^+$ branching fraction that is used as a normalization. In addition, the charge asymmetries of $B^\pm \rightarrow \eta' K^\mp$ and $B^\pm \rightarrow \phi K^\mp$, which are control channels, are measured to be $(-0.2 \pm 1.3)\%$ and $(+1.7 \pm 1.3)\%$, respectively. All results are consistent with theoretical expectations.

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Hadronic decays of beauty hadrons into final states without charm quarks (charmless decays) are suppressed in the standard model of elementary particles. They proceed predominantly through $b \rightarrow u$ transitions, mediated by the emission of a virtual $W^\pm$ boson, and $b \rightarrow s$ transitions, mediated by the exchange of a virtual $W^\pm$ boson and a virtual quark. The respective “tree” and “penguin” amplitudes are of similar size, allowing for possible large quantum interference effects measurable as charge-parity $(CP)$ violating asymmetries. New particles not described in the standard model may contribute with additional amplitudes, and therefore affect both the decay rates and the $CP$ asymmetries [1]. The $B^\pm \rightarrow \eta' K^\pm$ and $B^0 \rightarrow \eta' K^0$ decays, first observed by the CLEO Collaboration [2], have some of the largest branching fractions among all charmless hadronic $B$-meson decays [3]. (Charge conjugation of neutral $B^0$, mesons is implied throughout this Letter. The notations $\eta'$ and $\phi$ refer to the $\eta' (958)$ and $\phi(1020)$ mesons, respectively.) Studies of such decays, conducted so far mostly at $e^+e^-$ colliders operating at the $\Upsilon(4S)$ resonance, provide accurate measurements of integrated $[4,5]$ and time-dependent $[6,7]$ $CP$-violating asymmetries in charmless hadronic $B^\pm$ and $B^0$ meson decays, and are useful to look for deviations from standard model predictions.

Charmless hadronic $B^0_s$ decays are poorly known, in particular decays to a pair of unflavoured neutral mesons $[8,9]$, but have been extensively studied in the framework of QCD factorization $[10–12]$, perturbative QCD $[13]$, soft collinear effective theory $[14]$, and flavour SU(3) symmetry $[15]$. The decay $B^0_s \rightarrow \eta' \eta'$ is expected to have a relatively large branching fraction, similar to that of its SU(3) counterpart $B \rightarrow \eta' K$; predictions range between $14 \times 10^{-6}$ and $50 \times 10^{-6}$, and have large uncertainties $[10–15]$. The $\eta' \eta'$ final state is a pure $CP$ eigenstate. Decays to this final state of $B^0_s$ and $\bar{B}^0_s$ mesons flavor tagged at production may therefore be used to investigate time-dependent $CP$ asymmetries in a complementary way to the measurements in $B^\pm \rightarrow \phi \phi$ [16], but without the need for an angular analysis.

In this Letter, we present the first observation of the $B^0_s \rightarrow \eta' \eta'$ decay. Its branching fraction is measured using the known $B^\pm \rightarrow \eta' K^\pm$ and $B^\pm \rightarrow \phi K^\pm$ decays as calibration channels. The $CP$ asymmetries of the calibration channels are also measured, relatively to the $B^\pm \rightarrow 1/\sqrt{2} K^\pm$ channel. All these measurements use proton-proton ($pp$) collisions corresponding to 3.0 fb$^{-1}$ of integrated luminosity, of which 1.0 (2.0) fb$^{-1}$ was collected in 2011 (2012) at a center-of-mass energy of 7 (8) TeV with the LHCb detector.

The LHCb detector [17] is a single-arm forward spectrometer at the LHC covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high-precision tracking system, two ring-imaging Cherenkov detectors used to distinguish different types of charged hadrons, a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter, and a muon system. The trigger [18] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies event reconstruction using information from all the detector subsystems.

Signal $B^0_s \rightarrow \eta' \eta'$, $B^\pm \rightarrow \eta' K^\pm$, and $B^\pm \rightarrow \phi K^\pm$ candidates are reconstructed through the decays $\eta' \rightarrow \pi^+ \pi^- \gamma$ and $\phi \rightarrow K^+ K^-$. Selection requirements are chosen to be as similar as possible for the three channels and are optimized for $B^0_s \rightarrow \eta' \eta'$, maximising the figure of merit $e/[\alpha/2 + \sqrt{B}]$ [19], where $e$ is the efficiency for selecting simulated signal events, $B$ is the number of background events in the signal region estimated from the mass sidebands, and $\alpha = 5$.

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*Full author list given at the end of the article.

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is the target significance of the possible signal. The
requirements on the $\phi$ meson and on the charged kaon
associated with the $\eta'$ or $\phi$ resonance in the candidate $B^\pm$
decays, which is referred to as the bachelor kaon, are
chosen to minimize the relative statistical uncertainty on the
$B^\pm \to \phi K^\mp$ signal yield.

Charged particles are required to be inconsistent with
originating from a primary $pp$ interaction vertex (PV) and
to have a transverse momentum ($p_T$) with respect to the
beam line in excess of 0.25 GeV/c, while bachelor kaons
must have $p_T > 1.2$ GeV/c. Particle identification algo-
rithms are applied to distinguish kaons from pions, and
photons from electrons [20]. Photons are required to have
$p_T > 0.5$ GeV/c. The intermediate $\eta'$ ($\phi$) resonances
must have $p_T > 1.5(0.5)$ GeV/c and momentum
$p > 4$ GeV/c. The $\pi^+\pi^-$ invariant mass in candidate $\eta'$
decays must exceed 0.56 GeV/$c^2$. $B$-meson candidates
must have $p_T > 4$ GeV/c. Topological variables are used
to isolate the signal, such as the angle between the
reconstructed $B$ momentum and the vector pointing from
the PV to the $B$ decay vertex (required to be smaller than
10 mrad), and the distance of closest approach to the PV of
the $B$ trajectory (required to be less than 0.04 mm).

Reconstructed invariant masses of the $B^\pm$, $B^0$, $\eta'$, and $\phi$
candidates are required to be in the ranges $5000 < m_{B^\pm} < 5600$ MeV/$c^2$, $5000 < m_{B^0} < 5500$ MeV/$c^2$, $880 < m_{\eta'} < 1040$ MeV/$c^2$ and $1000 < m_\phi < 1050$ MeV/$c^2$, respectively. Only candidates with a well reconstructed $B$ decay vertex are retained; in the events with multiple candidates ($\leq 5\%$), the candidate with the smallest vertex $\chi^2$
is kept.

The $B^0 \to \eta'\eta'$ signal yield is determined from a multi-
dimensional unbinned extended maximum likelihood fit to
the sample of $B^0 \to \eta'\eta'$ and $B^\pm \to \eta'K^\mp$ candidates, using
the combined $\sqrt{s} = 7$ and 8 TeV data sets. The likelihood
is written as $L = \exp(-\sum_i N_i) \prod_i N_i \prod_j N_j \prod_l P_i$, where $N_i$
is the yield of fit component $j$ (signal or backgrounds), $P_i$
is the probability of event $i$ for component $j$, and $N$ is the
total number of events. The probabilities $P_i$ are expressed as
products of probability density functions (PDF) for the
invariant masses used as observables in the fit: the
$\eta'\eta'$ invariant mass ($m_{\eta'\eta'}$), the two randomly ordered
$\pi^+\pi^-\gamma$ invariant masses ($m_{\pi\pi\gamma}$) of the $B^0 \to \eta'\eta'$
candidates, and the $\eta'K^\mp$ and $\pi^+\pi^-\gamma$ invariant
masses ($m_{\eta'K}$ and $m_{\pi\pi\gamma}$) of the $B^\pm \to \eta'K^\mp$ candidates.
In the reconstruction of the $\pi^+\pi^-\gamma$ candidates, the known $\eta'$
mass $[3]$ is applied as a constraint to calculate the $m_{\eta'\eta'}$
and $m_{\eta'K}$ variables.

The $B^\pm \to \eta'K^\mp$ sample is described with three com-
ponents: the signal, and two combinatorial background components with and without an $\eta'$ resonance in the decay
chain. The $B^0 \to \eta'\eta'$ sample is modeled with seven components, three of which are significant: the signal, the
combinatorial background and partially reconstructed $b$-hadron decays without $\eta'$ resonances in the final state.

The remaining backgrounds, for which the event yields are
found to be consistent with zero, consist of two combina-
torial and two partially reconstructed components, each
involving only one resonant $\pi^+\pi^-\gamma$ candidate.

All the PDFs that peak at the $B$ or $\eta'$ mass are modeled by
Crystal Ball (CB) functions [21] modified such that both
the high- and low-mass tails follow power laws and account
for non Gaussian reconstruction effects. The parameters
used for the description of $m_{\eta'K}$ for the $B^\pm$ signal are free
in the fit, while all the parameters of $m_{\eta'\eta'}$ for the $B^0$
signal PDF are determined from simulation, except the CB width.
The ratio of the CB widths in $m_{\eta'K}$ and $m_{\eta'\eta'}$ is fixed to that
measured in simulation. The partially reconstructed back-
ground is described with an ARGUS function [22] con-
volved with a Gaussian resolution function of the same
width as the corresponding signal PDF, while the combi-
torial background is modeled with a linear function. A
common CB function is used for modeling all the $\eta'$
resonances, with mean and width free in the fit, while tail
parameters are determined from simulation. The mass
distribution of $\eta'$ candidates from random combinations
is modeled with an empirical quadratic function.

We observe $36.4 \pm 7.8$ (stat) $\pm 1.6$ (syst) $B^0 \to \eta'\eta'$
decays corresponding to a significance of 6.4 standard
deviations, including both statistical and systematic uncer-
tainties, discussed later. The significance is computed using
Wilk’s theorem [23], and is scaled by the ratio of the
statistical over the total uncertainties. The measured $B^0 \to
\eta'K^\mp$ yield is $8672 \pm 114$, where the uncertainty is statis-
tical only. Mass distributions are shown in Figs. 1 and 2,
with the fit results overlaid.

To measure the ratio of the branching fractions
$B(B^0 \to \eta'\eta')/B(B^\pm \to \eta'K^\mp)$, the fit is repeated taking
into account the different reconstruction efficiencies in the
7 and 8 TeV data sets. The four background components
with yields consistent with zero are neglected in this case.
The common parameters between the 7 and 8 TeV data sets
are the shape parameters and the ratio of branching
fractions. The ratio of branching fractions is related to
the ratio of yields according to

$$
\frac{\mathcal{B}(B^0 \to \eta'\eta')}{\mathcal{B}(B^\pm \to \eta'K^\mp)} = \frac{f_\eta f_s}{f_\eta f_s} \times \frac{1}{\mathcal{B}(\eta' \to \pi^+\pi^-\gamma)} \times \frac{N_l(B^0 \to \eta'\eta')}{N_l(B^\pm \to \eta'K^\mp)} \times \frac{e_l(B^0 \to \eta'K^\mp)}{e_l(B^\pm \to \eta'\eta')},
$$

(1)

where the subscript $l$ indicates the 7 TeV or 8 TeV data set,
the ratio of probabilities for a $b$ quark to produce a $B^0$ or $B^\pm$
meson is $f_\eta/f_s = 0.259 \pm 0.015$ [24], and the branching
fraction of the $\eta'$ decay is $\mathcal{B}(\eta' \to \pi^+\pi^-\gamma) = 0.291 \pm 0.005$
[3]. The ratio of efficiencies for reconstructing the
normalization and signal decay channels $e_l(B^\pm \to \eta'K^\mp)/
e_l(B^0 \to \eta'\eta')$ is determined from control samples (particle
Identification, photon reconstruction and hardware trigger on the signal) and simulation to be 8.46 ± 0.35 for the 7 TeV and 7.85 ± 0.26 for the 8 TeV data sets, including all experimental systematic uncertainties. The largest uncertainty in the determination of the efficiency ratio comes from the photon reconstruction efficiency. This efficiency is measured using $B^\pm \to J/\psi K^{*\pm}$ decays followed by $J/\psi \to \mu^+\mu^-$ and $K^{*\pm} \to K^\pm\pi^0 \to K^{\pm}\gamma\gamma$ [25], and a crosscheck is provided by the measurement of the ratio of branching fractions of the $B^0 \to \eta' K^\pm$ and $B^\pm \to \phi K^\pm$ control channels. The result of Eq. (1) is then

$$\frac{\mathcal{B}(B^0 \to \eta')}{\mathcal{B}(B^\pm \to \eta' K^\pm)} = 0.47 \pm 0.09(\text{stat}) \pm 0.04(\text{syst}).$$

Contributions to the systematic uncertainties are summed in quadrature leading to a total systematic uncertainty on the $B^0 \to \eta' K^\pm$ signal yield (ratio of branching fractions) of 1.6 (0.041). The uncertainties on $f_s/f_d$, $\mathcal{B}(\eta' \to \pi^+\pi^-\gamma)$, $\varepsilon(B^\pm \to \eta' K^\pm)/\varepsilon(B^0 \to \eta')$, and on the values of fit model parameters fixed from simulation, lead to a systematic uncertainty of 0.7 (0.038), while a variation of the PDF models leads to an uncertainty of 1.4 (0.007). The fit bias, evaluated in simulation, is consistent with zero, and its statistical uncertainty of 0.4 (0.005) is applied as a systematic uncertainty. Finally, an uncertainty of 0.014 is assigned to account for the neglected background components in the branching-fraction fit.

Using the known value $\mathcal{B}(B^\pm \to \eta' K^\pm) = (7.06 \pm 0.25) \times 10^{-5}$ [3], the branching fraction is measured to be $\mathcal{B}(B^0 \to \eta') = [3.31 \pm 0.64(\text{stat}) \pm 0.28(\text{syst}) \pm 0.12(\text{norm})] \times 10^{-5}$, where the third uncertainty comes from the $B^0 \to \eta' K^\pm$ branching fraction.

The $B^\pm \to \eta' K^\pm$ and $B^\pm \to \phi K^\pm$ charge asymmetries, $A_{CP}^{\pm} = (\Gamma^- - \Gamma^+)/(|\Gamma^- + \Gamma^+|)$, where $\Gamma^\pm$ is the partial width of the $B^\pm$ meson, are determined using the strategy adopted in Ref. [26]. For these measurements, we consider either events triggered on signal candidates (TOS events) or events triggered at the hardware stage independently of the signal candidate (non-TOS events). The raw asymmetries $A_{CP}^{\pm}$ are obtained from a fit to the positively and negatively charged candidates, and each subsample is further split into TOS and non-TOS events, to account for trigger-dependent detection asymmetries [26]. For each channel a two-dimensional fit of the mass distributions of the $B$ candidate and its neutral daughter is performed, and the four samples are fitted simultaneously.

The model in the $B^\pm \to \eta' K^\pm$ fit is the same as that used in the simultaneous $B^0 \to \eta' \eta'$ and $B^\pm \to \eta' K^\pm$ fit; the
$B^\pm \to \phi K^\pm$ model mirrors that of Ref. [26], except for the $m_{\phi K}$ signal PDF, which is described by the sum of a CB function and a Gaussian function. The shape parameters used to describe the peaking and partially reconstructed component PDFs are shared, while independent parameters are used for the combinatorial component PDFs in the trigger subsamples. In both fits, each component has four yields parametrized as $N_k = N_k(1+\Delta A_{CP,k})/2$, where $N_k$ and $\Delta A_{CP,k}$ are the yield and the raw asymmetry in each trigger category $k$, respectively.

The observed $B^\pm \to \eta' K^\pm$ ($B^\pm \to \phi K^\pm$) raw asymmetries and their statistical uncertainties are $-0.019 \pm 0.014$ ($+0.003 \pm 0.014$) and $-0.027 \pm 0.020$ ($-0.011 \pm 0.018$) for the TOS and non-TOS categories, respectively, the fraction of event in the TOS category being 63.8% (60.1%). The fitted mass spectra for the $B^\pm \to \phi K^\pm$ candidates are shown in Fig. 3.

In order to determine the $CP$ asymmetry, the raw asymmetry is corrected for the $B^\pm$ production asymmetry in $pp$ collisions, $A_p$, and for the bachelor $K^\pm$ detection asymmetry due to interactions with the detector matter, $A_{D,k}$. Under the assumption that these asymmetries are small, $A_{raw,k}$ is related to the $CP$ asymmetry $A_{CP}$ as $A_{raw,k} = A_{CP} + A_{D,k} + A_p$. Because the $CP$-violating asymmetry in $B^\pm \to J/\psi K^\pm$ is known precisely [3], the raw asymmetry in this decay is used to determine the sum of the detection and production asymmetries. The raw asymmetry of the $B^\pm \to J/\psi K^\pm$ decay is measured in a simultaneous fit to the $m_{J/\psi K^\pm}$ distributions of the positively and negatively charged candidates selected with similar criteria as for the signal modes. Independent fits are performed for events belonging to each trigger category. The fit model consists of a peaking signal component, described with the sum of a CB function and a Gaussian function, and a linear combinatorial background component.

The raw $B^\pm \to J/\psi K^\pm$ asymmetries, $-0.020 \pm 0.004$(stat) and $-0.011 \pm 0.003$(stat) for the TOS and non-TOS categories, respectively, are subtracted from the $B^\pm \to \eta' K^\pm$ or $B^\pm \to \phi K^\pm$ raw asymmetries for each trigger category. The weighted average of these asymmetry differences, $\Delta A_{CP} = A_{CP} - A_{CP}(B^\pm \to J/\psi K^\pm)$, is computed with weights given by the fractions of signal events in each of the two categories. The resulting asymmetry differences are $\Delta A_{CP}(B^\pm \to \eta' K^\pm) = -0.005 \pm 0.012$(stat) and $\Delta A_{CP}(B^\pm \to \phi K^\pm) = +0.014 \pm 0.011$(stat).

Three significant sources of systematic uncertainties are identified. The first accounts for the mass shape modeling, leading to an uncertainty on $\Delta A_{CP}$ of 0.021 $\times$ 10$^{-3}$ (0.20 $\times$ 10$^{-3}$) for the $B^\pm \to \eta' K^\pm$ ($B^\pm \to \phi K^\pm$) channel. To account for the different kinematic properties between the signal channels and the $B^\pm \to J/\psi K^\pm$ channel, $\Delta A_{CP}$ is measured in three independent subsamples selected according to the transverse momentum of the bachelor kaon, and their average, weighted by the number of events in each subsample, is computed. The difference from the result obtained in the default fit is 0.018 $\times$ 10$^{-2}$ (0.08 $\times$ 10$^{-2}$), which is assigned as a systematic uncertainty. Finally, the $CP$ measurements are repeated applying a geometrical requirement [26] to suppress possible detector edge effects. The associated systematic uncertainty is 0.13 $\times$ 10$^{-3}$ (0.05 $\times$ 10$^{-3}$).

Using the known $B^\pm \to J/\psi K^\pm$ $CP$ asymmetry, $A_{CP}(B^\pm \to J/\psi K^\pm) = +0.3 \pm 0.6 \times 10^{-2}$ [3], the asymmetries are measured to be $A_{CP}(B^\pm \to \eta' K^\pm) = -0.2 \pm 1.2$(stat) $\pm 0.1$(syst) $\pm 0.6$(norm) $\times 10^{-2}$ and $A_{CP}(B^\pm \to \phi K^\pm) = +1.7 \pm 1.1$(stat) $\pm 0.2$(syst) $\pm 0.6$(norm) $\times 10^{-2}$, where the third uncertainty comes from the $B^\pm \to J/\psi K^\pm$ $CP$ asymmetry. These results are compatible with the hypothesis of $CP$ symmetry and with the standard model predictions [12,27].

In conclusion, this Letter presents the first observation of the decay $B^\pm \to \eta' \eta'$, with a significance of 6.4 standard deviations, and the most precise measurements of $CP$-violating charge asymmetries in $B^\pm \to \eta' K^\pm$ and $B^\pm \to \phi K^\pm$ decays. The latter result supersedes the previous LHCb measurement [26]. The measured $B^\pm \to \eta' \eta'$ branching fraction, $\mathcal{B}(B^\pm \to \eta' \eta') = [3.31 \pm 0.64(stat) \pm 0.28(syst) \pm 0.12(norm)] \times 10^{-5}$, agrees with the theoretical predictions. This newly observed $B^\pm$ decay channel to a charmless $CP$ eigenstate opens possibilities for further
constraining the standard model with time-dependent CP asymmetry measurements.

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Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
School of Physics, University College Dublin, Dublin, Ireland
Sezione INFN di Bari, Bari, Italy
Sezione INFN di Bologna, Bologna, Italy
Sezione INFN di Cagliari, Cagliari, Italy
Sezione INFN di Ferrara, Ferrara, Italy
Sezione INFN di Firenze, Firenze, Italy
Laboratori Nazionali dell’INFN di Frascati, Frascati, Italy
Sezione INFN di Genova, Genova, Italy
Sezione INFN di Milano Bicocca, Milano, Italy
Sezione INFN di Milano, Milano, Italy
Sezione INFN di Padova, Padova, Italy
Sezione INFN di Pisa, Pisa, Italy
Sezione INFN di Roma Tor Vergata, Roma, Italy
Sezione INFN di Roma La Sapienza, Roma, Italy
Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
National Center for Nuclear Research (NCBJ), Warsaw, Poland
Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
Institute for High Energy Physics (IHEP), Protvino, Russia
Universitat de Barcelona, Barcelona, Spain
Universidad de Santiago de Compostela, Santiago de Compostela, Spain
European Organization for Nuclear Research (CERN), Geneva, Switzerland
Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
Physik-Institut, Universität Zürich, Zürich, Switzerland
Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
University of Birmingham, Birmingham, United Kingdom
H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, University of Warwick, Coventry, United Kingdom
STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Imperial College London, London, United Kingdom
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
Department of Physics, University of Oxford, Oxford, United Kingdom
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
University of Cincinnati, Cincinnati, Ohio 45221, USA
University of Maryland, College Park, Maryland 20742, USA
Syracuse University, Syracuse, New York 13224, USA
Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil (associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)
Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China (associated with Center for High Energy Physics, Tsinghua University, Beijing, China)
Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia (associated with LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France)
Institut für Physik, Universität Rostock, Rostock, Germany (associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)
Also at Università di Firenze, Firenze, Italy.
Also at Università di Ferrara, Ferrara, Italy.
Also at Università della Basilicata, Potenza, Italy.
Also at Università di Modena e Reggio Emilia, Modena, Italy.
Also at Università di Milano Bicocca, Milano, Italy.
Also at LIFAEELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.
Also at Università di Bologna, Bologna, Italy.
Also at Università di Roma Tor Vergata, Roma, Italy.
Also at Università di Genova, Genova, Italy.
Also at Scuola Normale Superiore, Pisa, Italy.
Also at Università di Cagliari, Cagliari, Italy.
Also at Politecnico di Milano, Milano, Italy.
Also at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.
Also at AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.
Also at Università di Padova, Padova, Italy.
Also at Hanoi University of Science, Hanoi, Viet Nam.
Also at Università di Bari, Bari, Italy.
Also at Università degli Studi di Milano, Milano, Italy.
Also at Università di Roma La Sapienza, Roma, Italy.
Also at Università di Pisa, Pisa, Italy.
Also at Università di Urbino, Urbino, Italy.
Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.